Report of the Working Group on the Composition of Ultra High Energy Cosmic Rays

R. Abbasi[1], J. Bellido[2], J. Belz[1], V. de Souza[3], W. Hanlon[1], D. Ikeda[4], J.P. Lundquist[1], P. Sokolsky[1], T. Stroman[1], Y. Tameda[5], Y. Tsunesada[6], M. Unger[7,8], A. Yushkov[9] for the Pierre Auger Collaboration[10] and the Telescope Array Collaboration[11]

[1]*Department of Physics and Astronomy, University of Utah, 115 South 1400 East, Salt Lake City 84112, U.S.A.*
[2]*University of Adelaide, Adelaide, S.A., Australia*
[3]*Instituto de Física de São Carlos, Universidade de São Paulo, São Carlos, Brasil*
[4] *Institute for Cosmic Ray Research, University of Tokyo, Kashiwa, Chiba, Japan*
[5] *Faculty of Engineering, Kanagawa University, Yokohama, Kanagawa, Japan*
[6] *Graduate School of Science and Engineering, Tokyo Institute of Technology, Meguro, Tokyo, Japan*
[7]*Center for Cosmology and Particle Physics, New York University, 4 Washington Place, New York, NY 10003*
[8]*Institut für Kernphysik, Karlsruher Institut für Technologie, Postfach 3640, 76021 Karlsruhe, Germany*
[9]*Institut für Physik, Universität Siegen , Walter-Flex-Str. 3, 57068 Siegen, Germany*
[10]`http://www.auger.org/archive/authors_2014_10.html`
[11]`http://www.telescopearray.org/index.php/research/collaborators`

E-mail: *jose.bellidocaceres@adelaide.edu.au, belz@cosmic.utah.edu*

For the first time a proper comparison of the average depth of shower maximum (X_{max}) published by the Pierre Auger and Telescope Array Observatories is presented. The X_{max} distributions measured by the Pierre Auger Observatory were fit using simulated events initiated by four primaries (proton, helium, nitrogen and iron). The primary abundances which best describe the Auger data were simulated through the Telescope Array (TA) Middle Drum (MD) fluorescence and surface detector array. The simulated events were analyzed by the TA Collaboration using the same procedure as applied to their data. The result is a simulated version of the Auger data as it would be observed by TA. This analysis allows a direct comparison of the evolution of $\langle X_{\mathrm{max}}\rangle$ with energy of both data sets. The $\langle X_{\mathrm{max}}\rangle$ measured by TA-MD is consistent with a preliminary simulation of the Auger data through the TA detector and the average difference between the two data sets was found to be $(2.9 \pm 2.7\ \text{(stat.)} \pm 18\ \text{(syst.)})$ g/cm^2.

KEYWORDS: UHECR 2014, cosmic rays, air shower, composition

1. Introduction

Composition is a central key to understand the origin of ultra-high energy cosmic rays. Large efforts in developing new detectors and analysis procedures have been made recently in order to improve our knowledge about the abundance of particles arriving at Earth. At the highest energies ($E > 10^{18}$ eV) the depth of shower maximum (X_{max}) is one of the most robust observables available to infer the composition. Currently, the Pierre Auger and the Telescope Array observatories measure

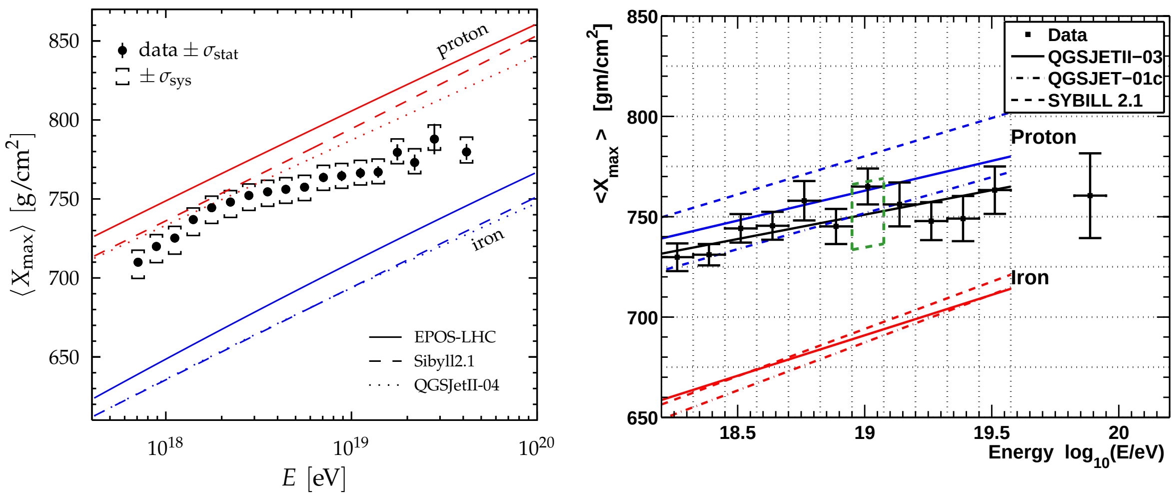

Fig. 1. $\langle X_{max} \rangle$ as measured by the Pierre Auger (left) and Telescope Array (right) Collaboration [2, 3]. The colored lines denote predictions of air shower simulation (note that different models are shown in the left and right panel, only Sibyll2.1 is the same). The black line on the right panel is a straight-line fit to the TA data.

X_{max} using fluorescence detectors. Despite the use of the same detection principle, a direct comparison of the data published by both collaborations is not straightforward.

The TA Collaboration publishes $\langle X_{max} \rangle$ values obtained from distributions folded with detector resolution and efficiency. The interpretation of the data is made possible by the publication of the Monte-Carlo prediction for proton and iron nuclei also folded with detector resolution and efficiency (Fig. 1, right). In the Auger Collaboration only certain shower geometries are selected for sampling almost unbiased X_{max} distributions. The corresponding $\langle X_{max} \rangle$ values are presented in the left panel of Fig. 1. In the Auger analysis, each selected geometry allows a wide enough range of X_{max} values to be observed within the fluorescence detector field of view boundaries. We will refer to this event selection as 'fiducial selection'. Besides that, the Auger Collaboration published $\sigma(X_{max})$ with detector resolution unfolded. This procedure allows the interpretation of the data (i.e. $\langle X_{max} \rangle$ and $\sigma(X_{max})$) using Monte Carlo predictions without the need to fold the detector properties into the predictions. The advantage of the TA analysis is that it does not require removing as many events, since this technique does not apply a fiducial selection.

The work reported here is a common effort of the Auger and TA Collaborations with the aim to provide the cosmic ray community a direct comparison of the $\langle X_{max} \rangle$ measurements taking into account the different approaches of each collaboration. Indirect comparisons of TA and Auger results were published in the first report of these series [1]. The disadvantage of indirect comparisons is that they depend on the particular hadronic interaction model that is used. The current analysis was performed in the following way. The Auger X_{max} distributions were fitted by a combination of four primary nuclei (proton, helium, nitrogen, iron) using events from air shower simulations. The abundances which best fit the Auger data were simulated through the TA-MD detector and analyzed by the TA Collaboration using the same procedure as applied to their data. This procedure resulted in the Auger data folded into the TA-MD detector. The Auger $\langle X_{max} \rangle$ folded with TA-MD analysis is shown in this paper in comparison to the TA-MD data as it is usually published.

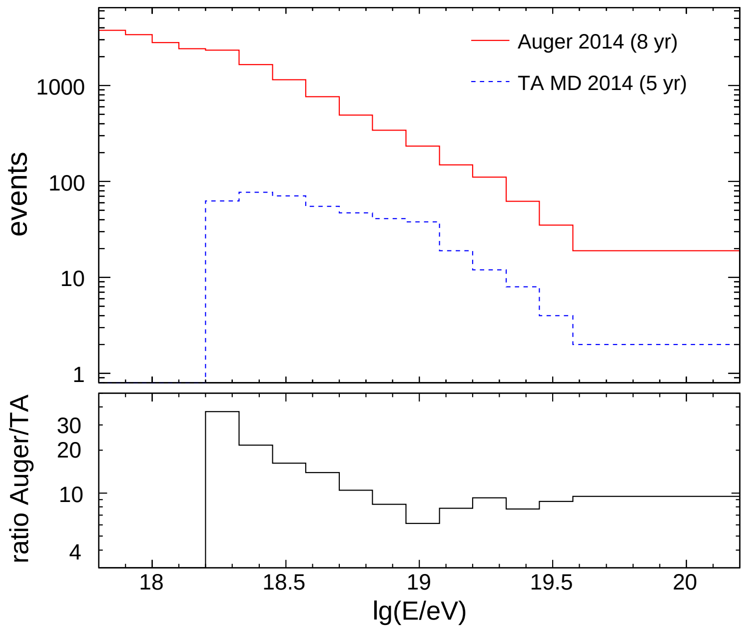

Fig. 2. Number of selected events for the Auger (solid red line) and TA (blue dashed line) analyses. The ratio of events is given in the lower panel.

2. Data Samples

The analysis presented here is based on the data measured by the Pierre Auger Observatory in the period from the 1st of December 2004 until 31st of December 2012. All measured events were analyzed as explained in reference [2]. The events were selected in order to guarantee good measurement conditions and a high-quality reconstruction. After that, the fiducial selection was applied. In total 19,947 events were considered for further analysis. The $X_{\max}$ values of these events were sampled in 18 energy bins starting at $\log(E/\mathrm{eV}) = 17.8$.

From the Telescope Array we use hybrid data collected with the MD fluorescence telescope and surface detector array over the period from the 27th of May 2008 to the 2nd of May 2013. The reconstruction and analysis applied to the data is described in [3]. The number of events which passed all cuts is 438, for which the mean $X_{\max}$ is shown in 12 energy bins above $\log(E/\mathrm{eV}) = 18.2$.

The number of events used for this comparison presented here is shown in Fig. 2 and the $X_{\max}$-resolution of the two experiments is presented in Fig. 3. As can be seen, the resolutions after cuts are comparable but it is worthwhile noting that the resolution quoted for the MD does not contain effects from the detector calibration and atmospheric monitoring. The systematic uncertainties on the $X_{\max}$ scale are compared in the right panel of Fig. 3 and they are ≤ 10 g/cm^2 and 16 g/cm^2 for the Auger and TA analyses respectively.

3. Analysis

Due to the different analysis approaches of the TA and Pierre Auger Collaborations it is not possible to compare the published values of $\langle X_{\max}\rangle$ and $\sigma(X_{\max})$ directly. Whereas the moments of

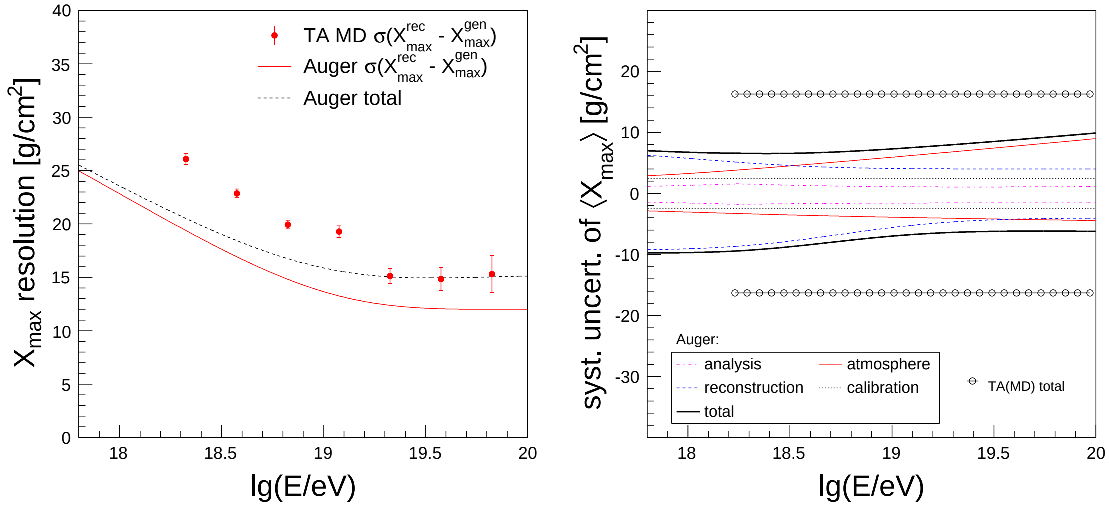

Fig. 3. $X_{\max}$ resolution (left) and systematics of the $X_{\max}$ scale (right) for the Auger and TA analyses.

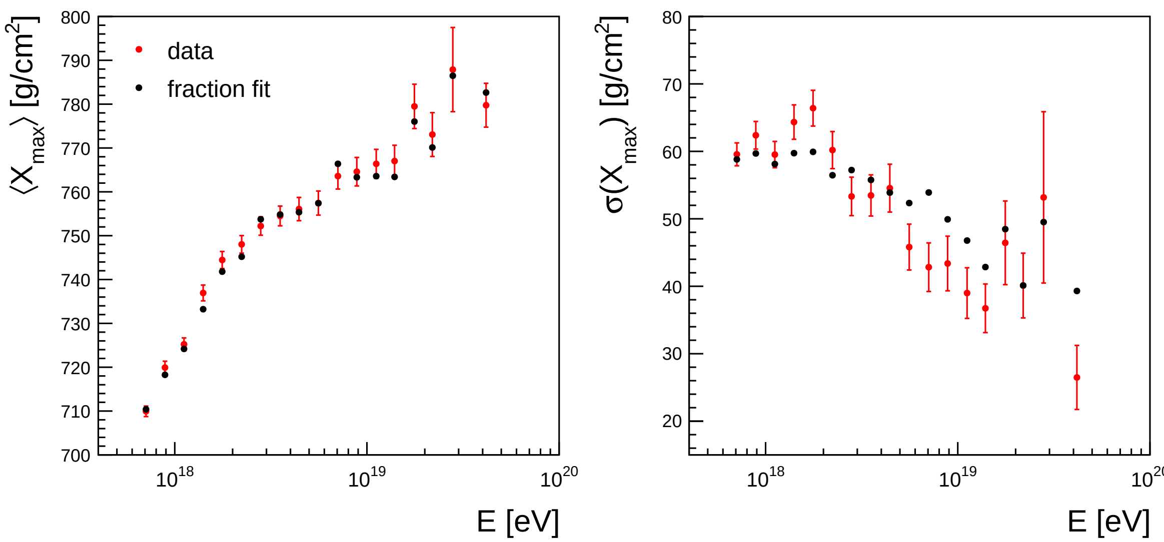

Fig. 4. Moments of the fitted $X_{\max}$ distributions using QGSJETII-03 (black markers) and $X_{\max}$ moments measured by the Pierre Auger Collaboration (red circles with statistical error bars), see text.

the $X_{\max}$ distribution published by the Pierre Auger Collaboration are close to the true moments (moments of f_{true} in Eq. (1)), the TA collaboration published the $\langle X_{\max}\rangle$ folded with the effects of the detector response and reconstruction (moments of f_{obs} in Eq. (1)).

The relation between the true and observed $X_{\max}$ distribution is

$$f_{\text{obs}}(X_{\max}^{\text{rec}}) = \int_0^\infty f_{\text{true}}(X_{\max})\,\varepsilon(X_{\max})\,R(X_{\max}^{\text{rec}} - X_{\max})\,\mathrm{d}X_{\max}, \tag{1}$$

i.e., the true distribution f_{true} is deformed by the detection efficiency ε and smeared by the detector

resolution R that relates the true $X_{\max}$ to the reconstructed one, $X_{\max}^{\text{rec}}$.

To be able to perform nevertheless a comparison of the two results, we need to establish what $\langle X_{\max}\rangle_{\text{obs}}$ would look like in the TA detector given the $X_{\max}$ distribution measured by Auger. For this purpose, we convolute a parametric description of f_{true} that is based on the Auger data with the TA detector simulation and apply the same reconstruction and analysis chain used for the TA data to this simulated data set (see [5] for a previous description of this method).

Technically, the parametric description of the $X_{\max}$ distribution is realized by providing a set of composition fractions as a function of energy that describe the $X_{\max}$ distributions measured by Auger. These fractions are obtained as described in [4] by a log-likelihood fit of templates of $X_{\max}$ distributions for different nuclear primaries as predicted by air shower simulations using a particular hadronic interaction model. It is worthwhile noting that the detector acceptance and resolution at a given primary energy depend mainly on $X_{\max}$ itself and only weakly on the primary particle type or hadronic interaction model via the invisible energy. Therefore, for the analysis presented here, it is only important that the resulting composition mix describes the data well and not which fractions of primaries are needed or which hadronic interaction model is used to obtain the model of the 'true' $X_{\max}$ distribution.

Here we used QGSJetII-03 [6] and a mix of four primary particles (proton, helium, nitrogen and iron) to obtain a model of true $X_{\max}$ distribution based on the Auger data. QGSJetII-03 is not included in the set of models studied by the Pierre Auger Collaboration to infer the primary composition [4] because it gives a worse description of LHC data than the re-tuned version QGSJetII-04 [7]. However, with neither version of QGSJetII it is possible to find a composition mix that gives a perfect description of the $X_{\max}$ distributions measured by Auger. The first two moments of the best fits with QGSJetII-03 and the Auger data are shown in Fig. 4. As can be seen, there is a good agreement regarding $\langle X_{\max}\rangle$, but there are deviations between the fitted and observed width of the distribution.

Ideally, this analysis should be performed with a combination of composition and hadronic interaction model that fits the Auger data well, such as Sibyll2.1 [8] or Epos-LHC [9] (see discussion in [4]). However, due to the lack of large air shower libraries other than QGSJetII-03 within the TA Collaboration, we performed the analysis with this model for practical reasons. Since the deviations between the moments of the data and the ones of the fitted distributions are on average at the 5 g/cm^2 level, this approach is expected to give only a small bias in the predicted observed distributions.

In detail, the analysis proceeds as follows: the composition mix is processed using the Telescope Array hybrid reconstruction analysis software. Showers are generated by CORSIKA and the trigger response of the surface detector is simulated. The generated longitudinal shower profile is fitted to a Gaisser-Hillas function to determine the shower parameters and a profile based on these parameters is generated. The TA fluorescence detector response including atmospheric, electronics, and geometrical acceptance is then simulated. Subsequently the event geometry is fitted via the fluorescence profile and the shower-detector plane is measured. A fit to hybrid shower geometry is performed which combines the timing and geometric center of charge of the surface detector array, with the timing and geometry of the fluorescence detector that observed the event. This step is what makes the event a hybrid event. If either the surface or fluorescence detector fail to trigger in an event, it is not processed any further, otherwise the shower profile is fitted via a reverse Monte Carlo method where the atmosphere, electronics, and geometrical acceptance of the shower are fully simulated.

The resulting effect of the folding of protons and the parametric Auger distributions with the TA detector response, reconstruction and analysis on the $\langle X_{\max}\rangle$ of Auger is shown in Fig. 5. As can be seen, the observed mean is smaller than the unbiased mean.

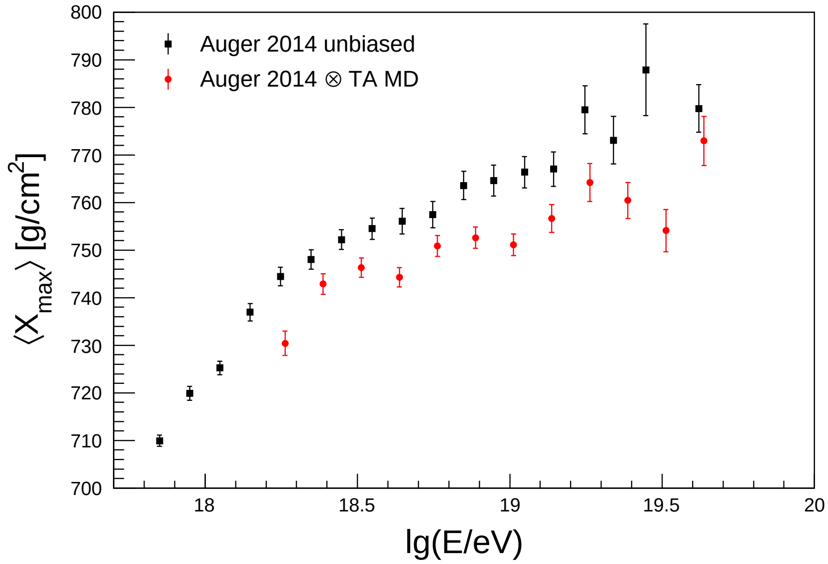

Fig. 5. Effect of the MD detector acceptance on X_{max}. The $\langle X_{max} \rangle$ of an X_{max} distribution describing the Auger data before and after the MD acceptance are shown as solid squares and circles respectively. The error bars denote the statistical uncertainties of the Auger result in case of the squares and the statistical uncertainties due to the limited MC statistics in the case of the circles.

4. Results and Discussion

The $\langle X_{max} \rangle$ as measured by TA using the MD fluorescence telescope and the Auger result folded with the TA acceptance are shown in Fig. 6. Their compatibility is quantified with a bin-by-bin comparison excluding the highest-energy data point of each experiment which are at different energies. Using only the statistical uncertainties yields a χ^2/Ndf of 10.7/11 with $P(\chi^2 \geq 10.7|11) = 0.47$. The average difference of the data points is $(2.9 \pm 2.7\ \text{(stat.)} \pm 18\ \text{(syst.)})$ g/cm^2 with a χ^2/Ndf of 9.5/10 ($P = 0.48$). It can be concluded that the two data sets are in excellent agreement, even without accounting for the respective systematic uncertainties on the X_{max} scale. However, in the present study we did not take into account a possible difference in the energy scale of the two experiments. The comparison of the energy spectra at the ankle region suggests that the energy scale of TA is about 13% higher than the one of the Pierre Auger Observatory [10]. But since the elongation rate of the folded Auger data is small ($\sim$ 19 g/cm^2/decade), the effect of such an energy shift on the comparison is expected to be at the level of a few g/cm^2. For a more precise evaluation it is required to take into account the energy dependence of the acceptance of TA. Nevertheless, it is to be expected that the increased difference between the two data sets once the energy scale shift is taken into account will be much smaller than the systematic uncertainties on the X_{max} scale of $\leq$ 10 g/cm^2 and 16 g/cm^2 for the Auger and TA analyses respectively.

5. Conclusions

In this paper we presented a comparison between the data on $\langle X_{max} \rangle$ as measured by the Pierre Auger and Telescope Array Collaborations. An adequate comparison was achieved by taking into

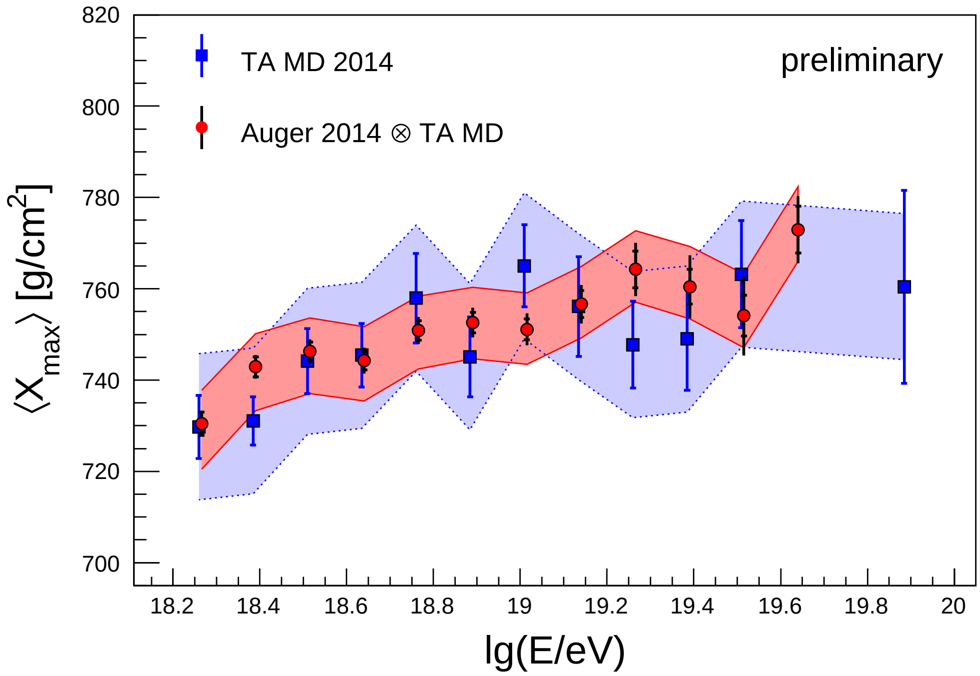

Fig. 6. Comparison of $\langle X_{\max}\rangle$ as measured with the MD of TA (blue squares) and the $\langle X_{\max}\rangle$ of the Auger data folded with the MD acceptance. The data points were slightly shifted horizontally for better visibility. In the case of the Auger points (red circles), the inner error bars denote the statistical uncertainty of the measurement and the total error bar also includes contributions from the limited statistics of simulated events used for the folding. The colored bands show the systematic uncertainties of the $X_{\max}$ scales of each experiment.

account that the $\langle X_{\max}\rangle$ published by Auger is corrected for detector effects, whereas the $\langle X_{\max}\rangle$ published by TA includes detector effects. In the future, we intend to improve the parametric description of the Auger $X_{\max}$ distributions and the evaluation of the effect of the relative energy scale uncertainty. Nevertheless, from the preliminary comparison presented here we conclude that the data of the two observatories are in good agreement.

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